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Search for Pair Production of Third-Generation Leptoquarks and Top Squarks in pp Collisions at $\sqrt{s} = 7$ TeV

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Results are presented from a search for the pair production of third-generation scalar and vector leptoquarks, as well as for top squarks in R-parity-violating supersymmetric models. In either scenario, the new, heavy particle decays into a τ lepton and a b quark. The search is based on a data sample of pp collisions at $\sqrt{s} = 7$ TeV, which is collected by the CMS detector at the LHC and corresponds to an integrated luminosity of 4.8 fb^{-1}. The number of observed events is found to be in agreement with the standard model prediction, and exclusion limits on mass parameters are obtained at the 95% confidence level. Vector leptoquarks with masses below 760 GeV are excluded and, if the branching fraction of the scalar leptoquark decay to a τ lepton and a b quark is assumed to be unity, third-generation scalar leptoquarks with masses below 525 GeV are ruled out. Top squarks with masses below 453 GeV are excluded for a typical benchmark scenario, and limits on the coupling between the top squark, τ lepton, and b quark, λ'_{333} are obtained. These results are the most stringent for these scenarios to date.

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Many extensions [1–6] of the standard model (SM) predict new scalar or vector bosons, called leptoquarks, which carry nonzero lepton and baryon numbers, as well as color and fractional electric charge. Such particles are motivated by a unified description of quarks and leptons. The combination of both baryon and lepton numbers implies that leptoquarks can mediate quark-lepton transitions, and leptoquarks decay into a quark and a lepton (with model-dependent branching fractions). For leptoquark masses that are within reach of current collider experiments, limits on flavor-changing neutral currents, i.e., processes that change quark flavor but not electric charge, along with limits on other rare processes [7], favor leptoquarks that couple to quarks and leptons within the same SM generation.

The dominant pair production mechanisms for leptoquarks at the Large Hadron Collider (LHC) are gluon-gluon fusion and quark-antiquark annihilation and the cross sections for these processes depend only on the leptoquark mass and spin. The results are interpreted in the context of models with either scalar leptoquarks (LQ) or vector leptoquarks (VLQ).

Supersymmetry (SUSY) is an attractive extension of the SM because it can resolve the hierarchy problem [8] without unnatural fine-tuning, if the mass of the supersymmetric partner of the top quark (top squark, or stop) is not too large [9]. In this scenario, the large mixing angle between the left-chiral and right-chiral stops ($\tilde{t}_L$ and $\tilde{t}_R$), which arises from the large top Yukawa coupling to the Higgs boson, can produce two mass eigenstates, $\tilde{t}_1$ and $\tilde{t}_2$, with a large mass splitting. Thus, $M_{\tilde{t}_1}$ can be substantially smaller than the masses of the other scalar SUSY particles. This light-stop scenario can be realized in both R-parity-conserving (RPC) and R-parity-violating (RPV) SUSY models, where R-parity is a new, multiplicatively conserved quantum number [10] that distinguishes SM and SUSY particles. Most previous searches for the light stop have been performed in the context of RPC models, in which the presence of two undetected particles (the lightest supersymmetric particles) generates a signature with large missing transverse momentum. If R-parity is violated, however, supersymmetric particles can decay into final states containing the standard model particles only. These signatures are not considered in most searches [11,12].

At the LHC, a $\tilde{t}_1\bar{\tilde{t}}_1$ pair is produced via strong interactions. When the masses of the supersymmetric partners of the gluon and quarks, excluding the top quark, are large, the stop pair production cross section is similar to that of the third-generation LQ. The cross section also depends on the first-generation squark mass and the stop mixing angle because of loop corrections, but the contribution from these diagrams is less than 2%. Trilinear RPV operators allow the lepton-number-violating decay $\tilde{t}_L \rightarrow \tau b$ [10] with a coupling λ'_{333}, resulting in the same final state as for third-generation LQ decay, with similar kinematics.

In this Letter, a search is presented for pair production of third-generation leptoquarks or stops, each decaying to a τ lepton and a b quark, using pp collision data at

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$\sqrt{s} = 7$ TeV. The data sample has been recorded by the CMS detector and corresponds to an integrated luminosity of 4.8 fb^{-1}. One of the τ leptons in the final state is required to decay leptonically, $\tau \to \ell \nu_\ell \nu_\tau$, where ℓ can be either a muon or an electron, referred to as the light lepton below. The other τ lepton is required to decay to hadrons (τ_h), $\tau \to \mathrm{hadrons} + \nu_\tau$. These requirements result in two possible final states referred to as $e\tau_h b\bar{b}$ and $\mu\tau_h b\bar{b}$. The experimental signature is characterized by an energetic electron or muon, a τ_h, and two jets produced by the hadronization of quarks (b jets). For the pair production of leptoquarks or stops, the scalar sum of the transverse momenta (p_T) of the decay products, $S_\mathrm{T} \equiv p_\mathrm{T}^{\tau_h} + p_\mathrm{T}^{\ell} + p_\mathrm{T}^{b_1} + p_\mathrm{T}^{b_2}$, is expected to be large, as is the invariant mass of each system containing a b jet and a τ lepton originating from the same heavy particle.

No evidence for third-generation LQ or stops has been found in previous searches, using a final state with τ_h, light lepton, and two b jets. The most stringent lower limits on LQ and stop masses are 210 GeV [13] and 153 GeV [14], respectively. A search performed by the CMS Collaboration has excluded the existence of a third-generation LQ with an electric charge of $\pm 1/3$ and mass below 450 GeV, assuming 100% branching fraction to a b quark and a ν_τ [15]. Indirect bounds [16] exclude the region $\lambda'_{333} > 0.26$ for $M_{\tilde{t}_1} \sim 100$ GeV.

The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter, providing a field of 3.8 T. A silicon pixel and strip tracker, which allows the reconstruction of the trajectories of charged particles within the pseudorapidity range $|\eta| < 2.5$, where $\eta = -\ln[\tan(\theta/2)]$ and θ is the polar angle with respect to the counterclockwise proton beam, are the innermost parts of the CMS detector. The tracker is surrounded by a calorimetry system, consisting of a lead-tungstate crystal electromagnetic calorimeter (ECAL) and a brass-scintillator hadron calorimeter, which measures particle energy depositions for $|\eta| < 3$. The tracker and ECAL are placed within the superconducting solenoid. Muons are identified in gas-ionization detectors embedded in the steel flux return yoke of the magnet. Collision events are selected using a two-tiered trigger system. A more detailed description of the CMS detector can be found in Ref. [17].

Events are collected using triggers requiring the presence of an electron or a muon and a τ_h with transverse momentum thresholds ranging between 12–20 GeV and 15–20 GeV, respectively, depending on the data-taking period. Electrons are reconstructed using the tracker and fully instrumented barrel ($|\eta| < 1.44$) or end cap ($1.57 < |\eta| < 2.1$) regions of the ECAL. Selected electrons are required to have transverse momenta $p_\mathrm{T} > 30$ GeV, an electromagnetic shower shape consistent with that of an electron, and an ECAL energy deposition that is compatible with the track reconstructed in the tracker. Muons are required to be reconstructed by both the tracker and the muon spectrometer. Candidates are required to have $|\eta| < 2.1$ and $p_\mathrm{T} > 30$ GeV. A particle-flow (PF) technique [18] is used for the reconstruction of τ_h candidates. Information from all subdetectors is combined to reconstruct and identify final-state particles (PF candidates) produced in the collision. The PF candidates are used with the hadron-plus-strips algorithm [19] to reconstruct hadronic decays of τ leptons with one or three charged pions and up to two neutral pions. The reconstructed τ_h is required to have $p_\mathrm{T} > 50$ GeV and $|\eta| < 2.3$. The light lepton and τ_h are required to have opposite electric charge. To reduce background from additional proton-proton interactions in the same beam crossing (pileup), the light lepton and τ_h are required to originate from the same vertex. The criteria for association to the vertex are optimized to take into account the finite lifetime of the τ lepton and are efficient for selecting an electron or muon from its decay. Selected electrons, muons, and τ_h are required to be isolated from other PF candidates and to be separated by $\Delta R \equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} > 0.5$ for both the $e\tau_h b\bar{b}$ and $\mu\tau_h b\bar{b}$ channels. Here, $\Delta\phi$ is an azimuthal and $\Delta\eta$ is a pseudorapidity separation between the light lepton and τ_h.

Jets are reconstructed using PF candidates with the anti-kT algorithm [20] with a distance parameter of 0.5. An average contribution of pileup interactions is estimated and subsequently subtracted from the jet energy [21]. Selected jets are required to be within $|\eta| < 2.4$ and have $p_\mathrm{T} > 30$ GeV. Additionally, these jets must be separated from the selected light lepton and τ_h by $\Delta R > 0.5$. The selected events are required to have at least two jets identified as originating from b quark hadronization (b-tagged) using a displaced track counting algorithm, based on track impact parameter significance [22].

To discriminate between signal and background, the invariant mass of the τ_h and b jet ($M_{\tau_h,b}$) is required to be greater than 170 GeV. Of the two possible pairings of the τ_h and b jets, the one for which the invariant mass is closest to the invariant mass of the light lepton and the other b jet is chosen as an observable. After the final selection, the S_T distribution is used to search for an excess above the SM expectation.

The dominant sources of $\ell\tau_h b\bar{b}$ events from SM processes are the production of a W or Z boson associated with jets, where a jet is misidentified as a τ_h, and $t\bar{t}$ pair production. There is also a small contribution from Z bosons decaying to a pair of τ leptons, or to a pair of electrons or muons, where one of the electrons or muons is misidentified as the τ_h, and from single-top and diboson production processes.

The LQ signal is generated using the PYTHIA V6.420 [23] generator for a range of leptoquark masses M_LQ spanning 150 to 800 GeV. The MADGRAPH generator [24] interfaced with PYTHIA for hadronization and showering is used to model the dominant $t\bar{t}$ and W + jets backgrounds. These generators are also used to model the less significant Drell-Yan process Z/γ^* + jets. The single top production is modeled with the POWHEG [25] generator, and diboson processes are modeled with PYTHIA V6.4. All generated samples are interfaced with TAUOLA [26] for τ decay, passed through a full detector simulation based on GEANT4 [27] and the complete reconstruction chain used for data analysis. The VLQ and stop pair production processes are modeled using the CALCHEP [28] and PROSPINO [29] generators in order to compare the kinematics of their decay products with those from scalar LQ. The most precise available cross section calculations, either next-to-leading order (NLO) or next-to-NLO, are used to normalize the signal [30] and background processes [31,32].

The efficiencies of the trigger and final selection criteria for signal processes are estimated from the simulation. The identification efficiencies for leptons and b jets are found from data in different data-taking periods, and used where necessary to correct the event selection efficiency estimates from the simulation. The trigger efficiency for signal events with a LQ mass hypothesis of 550 GeV is close to 90% for both channels. The efficiency of the final selection is $[8.4 \pm 0.2(\mathrm{stat}) \pm 0.6(\mathrm{syst})]\%$ and $[13.3 \pm 0.3(\mathrm{stat}) \pm 0.9(\mathrm{syst})]\%$ for the $e\tau_h b\bar{b}$ and $\mu\tau_h b\bar{b}$ channels, respectively.

The $t\bar{t}$ background is estimated using simulation. The normalization and several kinematic distributions of the $t\bar{t}$ background are validated using events rejected by the $M_{\tau_h,b} > 170$ GeV criterion. Both the yield and the S_T distribution in this control region agree well with the data observation.

The number of W or Z background events containing a jet misidentified as a τ_h is estimated from data. The probability of misidentification is measured using events with a W boson produced in association with one jet passing τ_h selection criteria except the isolation requirement. The decay to electron or muon of the W boson is used. In the selected sample, the lepton is required to be well identified. The transverse mass $M_T = \{2p_T^\ell \not{E}_T[-\cos(\Delta\phi)]\}^{1/2}$ is required to be greater than 50 GeV. Here, p_T^ℓ and $\not{E}_T$ are the transverse momentum of the lepton, and the imbalance of the transverse energy in the event, respectively, and $\Delta\phi$ is the azimuthal angle between the lepton and the $\not{E}_T$ direction. To reduce the contribution from $t\bar{t}$ events, the candidate τ_h and the lepton are required to have the same electric charge. The probability to satisfy the final τ_h selection criteria is found to be independent of the transverse momentum and pseudorapidity of the candidate τ_h, and is $f = (2.44 \pm 0.53)\%$. The number of background events is given by $N_{\mathrm{bkg}} = N_{W_{\tau_h}} \times f/(1-f)$, where $N_{W_{\tau_h}}$ is the number of events in the control sample with well identified lepton, two b jets, and a τ candidate that passes the τ_h identification criteria but fails the isolation requirement and has opposite electric charge to that of the lepton. The contribution from $t\bar{t}$ background in this sample is subtracted. The S_T distribution for this background is determined from the Monte Carlo (MC) simulation. Because of statistical limitations on the MC samples, events with a lepton, a τ_h candidate, and two jets are used, and the jet p_T spectrum is reweighted to match that expected from b jets.

The small background processes, such as $Z \to \tau\tau$ and dibosons decaying into genuine τ_h or $Z \to ee$ and $Z \to \mu\mu$, with a light lepton misidentified as a τ_h, are estimated using the simulated data.

The estimations of the background and the signal efficiency are affected by systematic uncertainties. The uncertainty in the total integrated luminosity is 2.2% [33]. The uncertainty in the trigger and lepton efficiencies is 1–3%. The uncertainty assigned to the τ_h identification efficiency is 6%, while the uncertainty in the b-tagging efficiency and mistagging probability are 4% and 10%, respectively. Systematic uncertainties of 17% and 13% are assigned to the normalization of the $t\bar{t}$ background in the $e\tau_h b\bar{b}$ and the $\mu\tau_h b\bar{b}$ channels, respectively, based on the statistical uncertainties of the control sample and the uncertainties in the MC prediction, to which it is compared. The uncertainty in the cross section measurements for diboson production [34] is 30%, leading to a normalization uncertainty in the corresponding background rate. Owing to the statistical limitation on $Z \to \tau\tau/\ell\ell$ simulation, the uncertainty in these backgrounds is 70% and 30% for the $e\tau_h bb$ and $\mu\tau_h bb$, respectively. A 40% systematic uncertainty is assigned to the modeling of Z production in association with two b jets [35]. A 4% uncertainty, due to modeling of initial- and final-state radiation in the simulation, is assigned to the signal acceptance. Uncertainty due to the effect of pileup modeling in the MC simulation is estimated to be 3%. Jet energy scale (2–4% depending on pseudorapidity and transverse momentum) as well as energy scale (3%) and resolution (10%) uncertainties for τ_h which affect both the S_T distribution and the expected yields from the signal and background processes are taken into account.

Uncertainties due to the choice of parton distribution functions (PDF) of the proton lead to changes in the total cross section and the acceptance for both signal and background processes. PDF uncertainties in the theoretical cross section and on the final-state acceptance are calculated using the PDF4LHC [36] prescription, and are found to vary between 10–30% and 1–3%, respectively.

The number of observed events and the expected signal and background yields after the final selection are listed in Table I. Data are in good agreement with the SM background prediction. The S_T distribution of selected events in data and MC simulation is shown in Fig. 1. As the distribution of S_T predicted for the SM background is in good agreement with the distribution obtained in data, a limit is set on the product of the cross section for pair production of third-generation LQ and the square of

TABLE I. Estimated signal (LQ) and background yields and observed events in data after the final selection. The first value in the uncertainty on the yield is the statistical contribution and the second value is the systematic contribution. The PDF uncertainties are not included.

	$\mu + \tau_h b\bar{b}$ channel	$e + \tau_h b\bar{b}$ channel
$t\bar{t}$	$38.1 \pm 3.4 \pm 5.7$	$10.9 \pm 1.8 \pm 2.0$
W + jets/Z + jets	$11.6 \pm 0.1 \pm 3.6$	$8.4 \pm 0.1 \pm 2.6$
$Z(\tau\tau/ll)$	$5.0 \pm 1.6 \pm 2.1$	$2.1 \pm 1.5 \pm 0.9$
Diboson	$0.5 \pm 0.1 \pm 0.2$	$0.3 \pm 0.1 \pm 0.1$
Total background	$55.2 \pm 3.8 \pm 7.5$	$21.8 \pm 2.3 \pm 3.6$
Data	46	25
Signal (450 GeV)	$13.2 \pm 0.3 \pm 0.9$	$8.4 \pm 0.2 \pm 0.6$

the branching fraction for the decay to τ lepton and b quark. The modified frequentist construction CL_s [37] is used for limit calculation. A maximum likelihood fit is performed to the S_T spectrum simultaneously for both $e\tau_h b\bar{b}$ and $\mu\tau_h b\bar{b}$ channels, taking into account correlations between the systematic uncertainties. The limits as a function of the LQ mass are shown in Fig. 2. Assuming $\mathcal{B}(\mathrm{LQ} \to \tau b) = 1$, we exclude LQ with masses below 525 GeV at 95% confidence level (CL), in good agreement with the expected limit at 543 GeV. The difference between acceptance and selection efficiency for LQ and VLQ is less than a few percent [38]. Thus, the same observed limit can be used to extract the limit on a top SU(5) VLQ predicted by the model of Ref. [2]. Such vector leptoquarks with masses 760 GeV are excluded at 95% CL, in agreement with the expected limit of 762 GeV.

These results are interpreted as a limit on stop pair production with RPV decay. Assuming $\mathcal{B}(\tilde{t}_1 \to \tau b) = 1$, stop masses below 525 GeV are excluded. A limit is also extracted for a benchmark scenario, where the branching ratio $\mathcal{B}(\tilde{t}_1 \to \tau b)$ decreases as stop mass increases as R-parity-conserving decays open up. The minimal supersymmetric standard model parameters used in a benchmark scenario are heavy SU(2) gaugino $M_2 = 250$ GeV, heavy Higgsino mixing parameter $\mu = 380$ GeV, $\tan\beta = 40$, where β is the ratio of the Higgs vacuum expectation values, stop mixing angle $\theta = 0$, and $\lambda'_{333} = 1$. The limit on $\sigma\mathcal{B}(\tilde{t}_1 \to \tau b)^2$ as a function of stop mass is shown in Fig. 2. Using this benchmark, the R-parity-violating stop is excluded for masses below 453 GeV in agreement with an the expected exclusion mass of 474 GeV. Using the same parameter set, but two M_2 values (250 GeV and 1 TeV), limits are set on RPV

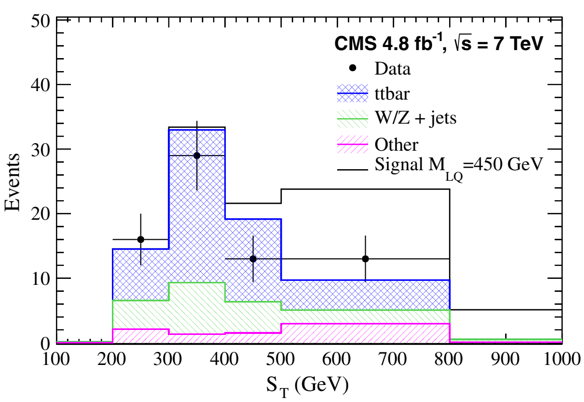

FIG. 1 (color online). The measured S_T distribution (points) compared to the stacked distribution of the SM backgrounds (shaded region) and a simulated $M_\mathrm{LQ} = 450$ GeV LQ signal (solid line) after the final selection.

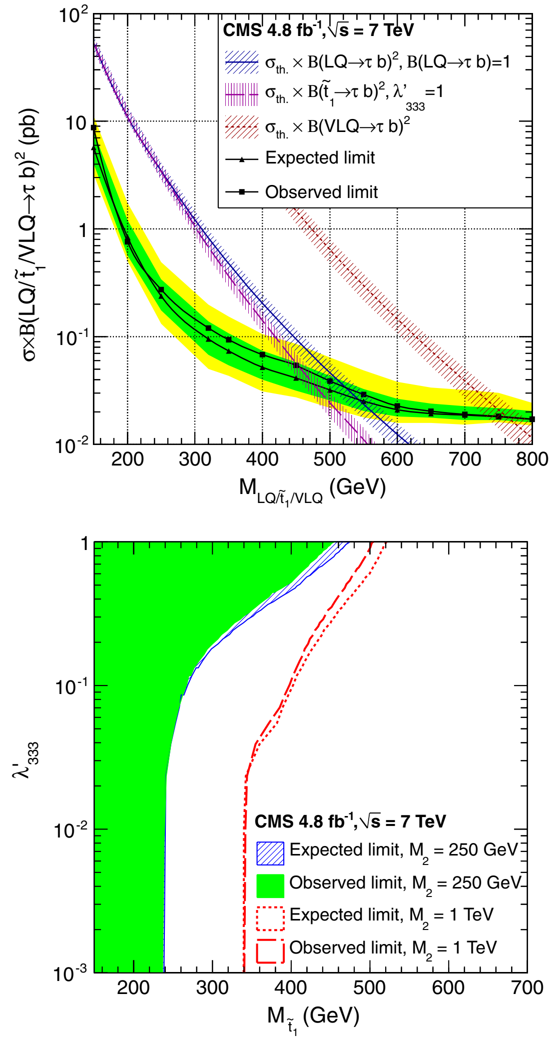

FIG. 2 (color online). Top: the expected and observed upper limit at 95% CL on the LQ ($\tilde{t}_1$, VLQ) pair production cross section times $\mathcal{B}(\mathrm{LQ}/\tilde{t}_1/\mathrm{VLQ} \to \tau b)$ as a function of the LQ ($\tilde{t}_1$, VLQ) mass. The $\pm1\sigma$ and $\pm2\sigma$ uncertainties on the expected limit are also shown as green (inner) and yellow (outer) bands around the expected limit. The blue (solid) curve, magenta (dashed) curve, and red (dotted) curve and the matching shaded bands represent the theoretical LQ, $\tilde{t}_1$, and VLQ pair production cross section and the uncertainties due to the choice of PDF and renormalization and factorization scales, respectively. Bottom: the expected and observed 95% CL limit on the RPV coupling λ'_{333} for $M_2 = 250$ GeV and $M_2 = 1$ TeV.

coupling λ'_{333} as a function of stop mass. The results are shown in Fig. 2. Top squarks with mass below 240 GeV (340 GeV) are excluded for $M_2 = 250$ GeV ($M_2 =$ 1 TeV) for all values of $\lambda'_{333} > \mathcal{O}(10^{-7})$, corresponding to a decay length of about 0.5 mm. Stops with very small values of λ'_{333} have been excluded by a different CMS analysis [39].

In summary, a search for pair production of third-generation scalar and vector leptoquarks and top squarks decaying in a RPV scenario has been presented. The search is performed in the final state including an electron or a muon, a hadronically decaying τ lepton, and two b jets. No excess above the SM background prediction is observed at high S_T. Assuming a 100% branching fraction to a τ lepton and a b quark, the existence of the scalar leptoquarks with masses below 525 GeV is excluded at 95% CL. The existence of SU(5) vector leptoquarks with masses below 760 GeV is also excluded at 95% CL. Limits are also set on top squark pair production with RPV decay. The limits are obtained on λ'_{333} as a function of stop mass, and stops with masses below 453 GeV are excluded for a benchmark scenario with $\lambda'_{333} = 1$. These limits are the most stringent to date, and the limits on λ'_{333} are the first direct limits that significantly improve previous indirect bounds.

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